

diameter of patent locked steel ropes, and the stiffening trusses of the two-hinged type. Alternative routes were shewn for the approaches on the Sydney side.

The premiums offered in connection with this competition were paid, but, in view of the above report, there was no tangible result so far as the erection of the bridge was concerned, and it was decided to hold a further competition limiting the structure to be tendered for to a certain definite length, and specifying the classes of materials to be used, and the unit stresses to be adopted.

PROPOSED SYDNEY HARBOUR BRIDGE.

SECOND COMPETITION, 1901-3.

On 25th March, 1901, a new Board was appointed to deal with the Bridge question, consisting of Mr. J. Davis, M. Inst. C.E., Chairman; and Messrs. H. Deane, M.A., M. Inst. C.E.; W. L. Vernon, F.R.I.B.A.; E. M. de Burgh, M. Inst. C.E.; Professor, W. H. Warren, M. Inst. C.E., M. Am. Soc. C.E.; and Mr. J. M. Purves, M.A.

The functions of this Board were defined as "a new Advisory Board in connection with the designs and the invitation of tenders for the North Shore Bridge." It should be noted that they had no power to act as a Royal Commission for the taking of evidence as to the necessity for the erection of a Bridge, nor were they instructed to enquire into the relative merits of Bridge and Tunnel schemes.

Evidence was taken in the first instance from a number of gentlemen interested in navigation, as to the clear height required for shipping under the main span, and also as to whether a central pier in the fairway would be objectionable. The Board then proceeded to consider a draft specification which had in the meanwhile been prepared by the author, acting under instructions from Mr. de Burgh, then Engineer for Bridges, and in May, 1901, tenders were advertised for a Bridge in accordance with this specification, as amended and finally decided upon by the Board. In passing, it may be mentioned that a paper describing how the unit stresses prescribed in this specification were arrived at, was submitted to the University Engineering Society, by Professor Warren and the author, in October, 1901.

The location of the Bridge was fixed between Dawes Point and McMahon's Point.

The advertisement calling for tenders first appeared in the Government Gazette of 17th May, 1901, as follows: "Tenders are now invited by the Government of New South Wales for the construction of a bridge over Sydney Harbour, embracing a main span of not less than 1,200 feet in the clear, with sufficient approach spans to make up a total length of 3,000 feet. The

headway to be provided is 170 feet in the clear above high-water mark of spring tides for at least the central 600 feet of the main span, but this may be diminished to 150 feet in the clear at the limits of the 1,200 feet fairway. The deck of the Bridge is to include a double line of railway, with two wood-blocked roadways, each of 30 feet, or one roadway of 60 feet between kerbs, (embracing a double line of tramway), and two footways each of 12 feet wide.

“The conditions of tendering, and a specification embracing full particulars as to the loading, unit stresses, and material to be adopted, together with plans, cross sections, and details of borings, may be obtained on application.”

There were also included conditions as to the supply of their own designs by tenderers, and as to deposit, etc. No premiums were offered in connection with this competition.

In response to this advertisement, 12 designs and tenders were submitted on 30th June, 1902, and on 15th August, 1902, the Advisory Board presented an interim report. In the meanwhile, about ten days before this date, the author had been taken ill, and for some months thereafter, Mr. J. J. C. Bradfield, M.E. Assoc. M. Inst. C.E., acted in his stead as Secretary to the Board.

Of the designs submitted, the Board, in their interim report, refer to three as deserving special consideration, and as from which the final choice should be made. These three designs, accompanied tenders from (1) Messrs. Sir William Arrol and Co., Ltd., and Head, Wrightson and Co., Ltd.; (2) The E. and C. Bridge Co.; and (3) Messrs. J. Stewart and Co. These three firms were accordingly asked to submit amended tenders based upon some modification of the loading prescribed in the original specification, and also upon an alteration in the design of the deck, whereby the two tram tracks were arranged for on an open deck instead of along the centre of the wood-blocked roadway, and the width of the latter was reduced from 60 feet to 35 feet wide between kerbs in consequence. The footways were also reduced from 12 feet to 10 feet each.

Designs and tenders from these three firms, and also from two other firms who had not been asked to tender, were received on 16th March, 1903.

The following particulars of the three designs referred to have been condensed from the Report of the Advisory Board:—

(1) SIR WILLIAM ARROL AND CO., LTD., AND HEAD, WRIGHTSON AND CO., LTD.—This design provided for a cantilever bridge with a main span of 1,300 feet, and two shore spans each of 350 feet. There were also eight lattice girder spans of from 80 feet to 246 feet each. This design was deemed unsuitable, chiefly from æsthetic considerations, and also on account of the

foundation for the main northern pier, which it was proposed to found on the clay at 62 feet below H.W.M., with a pressure of 5.6 tons per square foot.

(2) THE E. AND C. BRIDGE CO.—This design provided for a suspension bridge, with a main span of 1,300 feet between centres of towers, with one span of 320 feet, one of 210 feet, and 583 feet of steel trestle in the northern approach, and two spans each of 230 feet in the southern approach.

The top of towers was 351 feet about H.W.M. There were two cables on each side. The stiffening trusses were of the three hinged type. It was proposed to found the main northern pier upon the clay at 90 feet below H.W.M., where the total load was estimated at 5.62 tons per square foot. Even allowing for the weight of the water and overlying material at present above that depth, the Board was of opinion that the pressure allowed was too high, and though possessing undoubted merits from an engineering standpoint, this design was not considered to be as satisfactory in appearance as the design submitted with the tender from Messrs. Stewart and Co., while the cost was higher.

(3) MESSRS. J. STEWART AND Co.—The design which accompanied the tender from this firm was that which was recommended for acceptance, after modification as requested by the Advisory Board. In the Report of the Advisory Board, the authors of the design are described as follows:—"The design of the superstructure was carried out by the Vereinigte Maschinenfabrik Augsburg and Maschinenbaugesellschaft, Nurnberg, Dr. A. Rieppel, Chief Engineering Director, and Mr. F. Bohny, in charge of the Bridge Designing Bureau. Mr. Norman Selfe, M. Inst. C.E., of this city, acted as consulting engineer in connection with the modifications to the superstructure proposed by us, and was also responsible for the design of the substructure."

The design provided for a cantilever bridge with a main span of 1,350 feet between centres of piers. The northern shore arm of the cantilever was 580 feet, and the southern shore arm 500 feet long. On the northern side there were two approach spans of 270 feet each. In cross section, the main cantilevers were inclined towards each other on a batter of 1 in 8, while the top chords were curved in the form of a parabola, thus giving a pleasing appearance, which was enhanced by the artistic treatment of the towers. These latter were 400 feet above H.W.M., and in one tower provision was made for a pavilion at the top with a lift for the use of sightseers.

All the foundations were upon rock. The problem of the foundation for the main northern pier was a serious one. At this site the depth to rock was shewn by borings to be about

170 feet below H.W.M., or much in excess of the depth hitherto obtained in any bridge foundations. Overlying the rock are about 128 feet of clay, interspersed with sand, above which are 7 feet of silt, and 37 feet of water.

For the foundations of this pier no less than ten alternatives were submitted by the authors of the design accompanying the tender of Messrs. Stewart and Co.

Before coming to a decision as to the most suitable foundation, a test cylinder 6 feet in diameter was sunk to a depth of 90 feet below H.W.M., sealed with concrete, and loaded to a total pressure of 7.0 tons per square foot, neglecting skin friction, under which there was a settlement of 4.28 inches on eight days. With this information, obtained from the sinking of this cylinder before them, the Board decided that the formation below the bed of the harbour is quite unsuitable for founding the main pier upon, either direct, or supported piles, and were of opinion that this foundation should be carried to rock, which they considered could be done in the open by means of cofferdams. Failing that, they were satisfied that the foundation could be successfully carried out at a moderate cost by the use of the freezing process, as proposed in connection with one of the schemes submitted with Messrs. Stewart and Company's tender.

APPROACHES.—In addition to the main bridge, 3,000 feet long, for which tenders were invited, the Board had under consideration the approaches on either side of the harbour.

On the city side, these approaches were designed to give a connection with the City Railway scheme then proposed by Mr. Deane, in the vicinity of the Grosvenor Hotel, while the roadway and tramway across the bridge were taken down on a grade of 1 in 24 to Princes Street, near the Argyle Cut.

On the northern side the railway approach was designed to connect with the Milson's Point to Hornsby railway at Bay Road Station, and the roadway and tramway were taken on a grade of 1 in 28 to George Street, North Sydney.

Alternative designs for these approaches were prepared by the author, acting under a sub-Board consisting of Messrs. Deane and de Burgh. Under one scheme, the approach spans were to be of steel, while the alternative scheme, which was recommended, included approach spans of reinforced concrete arches faced with masonry.

RECOMMENDATION OF SYDNEY HARBOUR BRIDGE ADVISORY BOARD.

On 25th November, 1903, the Advisory Board presented their final report, which stated: "Of the tenders submitted, we have no hesitation in recommending for selection that of Messrs. J. Stewart and Co. for the supply and erection of the

bridge in accordance with their modified design already referred to. This is, in our opinion, the most satisfactory design received in either this or the previous competition, not only as regards its compliance with the conditions of tendering and provisions of the specification, but also in respect of the scientific design of the details of the superstructure, the substantial nature of the substructure, and its elegant appearance as a whole."

The estimated cost of the bridge and approaches is set down in this Report as £1,940,050, including land resumption. This included a total length of railway of 154 chains, and of roadway and tramway 82 chains.

BRIDGE SCHEMES CONSIDERED BY THE ROYAL COMMISSION ON COMMUNICATION BE- TWEEN SYDNEY AND NORTH SYDNEY, 1908-9.

The report of the Sydney Harbour Bridge Advisory Board brought the matter to such a stage that had the Government so determined, a contract for the construction of the bridge could have been let, and as the time required for construction was 5½ years, the work, if then initiated, should now have been completed. It happened, however, that the report of the Advisory Board was presented at a time of temporary financial depression, and no further action was taken towards the erection of the bridge, either by the Government then in power or by succeeding Governments.

During the 4½ years intervening between the presentation of the Advisory Board's report and the appointment of the Royal Commission referred to above, nothing of importance transpired with regard to the North Sydney connection, though several communications were received from persons desirous of being allowed to construct either a bridge or a tunnel.

On the 11th May, 1908, a Royal Commission was appointed "to make full and diligent enquiry into the expediency of providing increased and improved facilities of communication between Sydney and the suburbs on the northern side of Sydney Harbour, from the point of view of passenger, vehicular and freight traffic, and to suggest what, in your opinion, is the best practical method of establishing direct communication between the northern and southern side of the Harbour, which will, at the same time, avoid obstructions to Harbour navigation, and also the best route for direct communication."

This Commission consisted of Mr. M. E. Kernot, M. Inst. C.E., A. Am. Soc. C.E., Chairman; and Mr. H. Deane, M. Inst. C.E.; and Mr. C. N. J. Oliver, C.M.G., Commissioners. Mr. W. Renshaw, of the Public Works Dept., acted as Secretary.

The tunnel schemes dealt with by this Commission are referred to later.

With regard to the Bridge schemes, a number of proposals were submitted by gentlemen outside the Public Service, and various modifications of the Sydney Harbour Bridge Advisory Board's scheme were prepared by the author for the Commission, while the figures given in the report of that Board were brought up to date. This matter is referred to in the report of the Royal Commission as under:—

“The estimated cost of the bridge, recommended by the Sydney Harbour Bridge Advisory Board in 1903, which your Commissioners consider the best, was revised by Mr. Dare to allow for:—

- “1. Increased wage rates and prices of materials.
- “2. Customs duties levied on imported material.
- “3. Alterations in southern approaches.
- “4. Modifications in accommodation for traffic.

“The revised estimates are as follows:—

- “1. Total estimated cost of 1903 Bridge Scheme, with railway approach by Mr. Deane when Engineer-in-Chief for Railway Construction, providing in addition for the extension of the tramway on the city side to Wynyard Square £2,365,000
- “2. Increased estimate with same provision as No. 1, but with the southern railway approach altered to connect with and include a station under Wynyard Square, which would be substituted for the St. Phillip's Station on Mr. Hutchinson's City Railway Scheme. (The cost of this southern extension was supplied by Mr. Hutchinson) £2,581,000
- “3. Increased estimate if a second double line of railway is added to No. 1 £3,115,000
- “4. Reduced estimate, providing for only tramway, vehicular, and pedestrian traffic, omitting railway £1,592,000
- “5. Reduced estimate, providing for vehicular and pedestrian traffic only, omitting railway and tramway £1,470,000

“No. 1 is an estimate for the scheme recommended by the Advisory Board, with tramway extension. No. 2 is similar, except that the southern railway approach is extended to a station under Wynyard Square, where it could be linked up with a city railway. No. 3 provides for a second double line of railway which Mr. Johnson, Chief Commissioner for Railways,



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(As recommended by Advisory Board and Royal Commission.)

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thought it would be wise to add. No. 4 is a reduced estimate for the purpose of showing the effect of omitting the railway, which might be taken underground. No. 5 is a further reduced estimate, omitting both railway and tramway if both are taken underground.

“In the preparation of these estimates, the figures have been based on a tender under which it was proposed to import the steel, and it has been considered advisable to include the amount of Customs duty which would have to be paid on the material. No allowance has been made for any sum that may be refunded by the Commonwealth to the State, as the amount cannot be determined at present. It may be remarked that the importation of a large proportion of the steel work would have to be provided for, as it is beyond the capacity of the local steel works.”

The above figures, it should be noted, are for a bridge constructed under similar conditions of loading to those specified in connection with the second Bridge Competition, and are for a structure to carry a steam railway. The subway schemes referred to later are based upon electric traction for the railway.

For various reasons enumerated in their report, which was presented on 29th March, 1909, the Royal Commission did not favour the erection of a bridge, but recommended, instead, the construction of subways, which will now be referred to.

TUNNEL SCHEMES.

Before describing the schemes proposed for connecting with North Sydney by means of tunnels, reference will be made to subaqueous tunnels constructed in other parts of the world.

By far the greatest number of these have been driven by means of shields of various types, and nearly all within the past twenty years.

The subject of shield tunnelling is of such great interest, that it may perhaps be permitted to trace its development at some length, and to refer to some of the most notable examples of subaqueous tunnels constructed by this method.

SHIELD TUNNELLING.

Great Britain is the home of the Shield Tunnel. It was here that in 1818 the first patent was taken out by the famous Brunel for the “use of a casing or a cell, intended to be forced forward before the timbering which is generally applied to secure the work.” The drawings which accompany the patent shew an apparatus composed of small cells, each of which “may be forced forward independently of the contiguous one, so that each workman is supposed to operate in a small drift indepen-

dently of the adjacent one. . . . Each cell is to be moved or forced forward by any mechanical aid suitable to the purpose, but I give the preference to hydraulic presses. . . . The body or shell of the tunnel may be made of brick or masonry, but I prefer to make it of cast iron, which I propose to line afterwards with brickwork or masonry."

Here we have all the essentials of the modern shield-driven tunnel, with the exception of the use of compressed air, the application of which to structures in water-bearing strata was not brought into practical use until after the date of Lord Cochrane's patent in 1830.

The first use made of a shield for tunnelling purposes was by Brunel in the tunnel under the Thames, 1825-28. This tunnel was of rectangular section and of great size. The dimensions of the shield were 37 feet 6 inches wide and 22 feet 3 inches deep. The tunnel was constructed for vehicular purposes, and consisted of two brick lined tunnels with a pier between. It was subsequently employed as a railway tunnel in connection with the East London Railway. The shield was worked in twelve compartments, which were moved forward alternately by screw jacks. It is a matter of common history that after heroic struggles with a hitherto untried plant working in loose and water-bearing strata, the work was abandoned in 1828, but was recommenced in 1835, with an improved form of shield, and was brought to a successful conclusion in 1843.

Probably owing to the great cost of the first Thames tunnel, nothing further was done in this direction for many years, and it was not until 1869 that any other scheme involving the use of a shield for tunnelling purposes was put into operation. In that year, the Tower subway was driven in accordance with designs and under the direction of Mr. J. H. Greathead, the father of modern Shield Tunnelling. This tunnel, which is lined with cast iron, is 7 feet $1\frac{3}{4}$ inches outside diameter, and was driven throughout through London clay by means of a shield 4 feet 9 inches long, formed of wrought iron plates, and forced forward by screw jacks. Under the river there was a minimum covering of 22 feet, and the work was completed without any extraordinary difficulty.

In Appendix No. 1 is given a list of tunnels constructed under rivers or arms of the sea. For particulars of many of these the author desires to express his indebtedness to Copperthwaite's excellent book on "Tunnel Shields and the use of Compressed Air in Subaqueous Works." There are doubtless many other subaqueous tunnels not included in this list, but it may be taken as comprising the most prominent examples of most of the methods employed for this class of work.

Although the conditions in the proposed tunnel connection with North Sydney are such as to preclude the use of a

shield driven tunnel at the depth fixed upon by the Royal Commission, yet it may be of interest to refer to some typical tunnels constructed by this method.

CITY AND SOUTH LONDON RAILWAY.—After the construction of the Tower Subway, the next tunnel to be constructed by means of a shield was the City and South London Railway, the first of the London Tubes, which was carried out by Mr. Greathead between 1886 and 1890, and marks the commencement of a new era in shield tunnelling. This railway was constructed to relieve the street traffic of the metropolis. It is about $3\frac{1}{8}$ miles long, and is subaqueous throughout, though for practically the whole length, including the portion under the Thames, the tunnels were driven through London clay, which underlies the water-bearing strata. Two separate tunnels were employed, one for each line of way, lined with cast iron. The internal diameter of each tunnel was 10 feet 2 inches in the first section from the city under the Thames to the Elephant and Castle, and 10 feet 6 inches in the extension thence to Stockwell.

In Vol. 123, Proc. Inst. C.E., various advantages are claimed by Mr. Greathead for the use of two single line, in preference to one double line tunnel, the chief of these are (1) that where passing under narrow streets it would have been impossible to construct a double line tunnel. (All the London tubes are constructed under the public streets, and not under private property.) (2) Better gradients could be obtained, and less headway is required where passing under sewers, railways or the river. (3) Cheapness. (4) Better ventilation. (5) Less risk to building due to subsidence during construction.

At several points in both tunnels compressed air was used, for the first time in conjunction with a shield, in passing through water-bearing strata. The most notable instance was a length of about 200 yards near Stockwell, where the two tunnels were carried through coarse gravel and sand under a head of about 35 feet of water.

In passing, it may be noted that there is a great difference between sinking a vertical cylinder or caisson under compressed air, where the pressure is constant at any depth over the whole surface, and driving a horizontal tunnel, where the head of water varies by an amount corresponding with the diameter. In tunnels of large diameter, through water-bearing strata, great care and judgment are required to prevent a blow due to the extra pressure of air required to keep back the water over the lower portion of the face.

The shields employed in these tunnels were of the Greathead type, that for the 10 feet 6 inches section was 11 feet $4\frac{1}{2}$ inches diameter inside the skin, 6 feet 6 inches long over all. The skin consisted of two $\frac{1}{4}$ inch plates, secured together with

countersunk rivets, and stiffened at the front with heavy cast iron segments, extending right round the circumference. Between the cutting edge and these segments was interposed a $\frac{3}{4}$ inch diaphragm plate, in which was an opening 6 feet x 4 feet 6 inches, at the sides of which were fixed channel bars, in which could be dropped 3 inch planks for closing the shield, and at the same time to protect the tunnel against any sudden caving of the face. Secured to the cutting edge were steel cutter plates, which were adjustable by means of slotted holes so as to cut a larger section when passing round curves and to minimise friction, where required. The hydraulic rams were of cast steel, six in number, $6\frac{1}{2}$ inches diameter, operated by hand pumps, which gave a maximum pressure of 1,800 lb. per square inch, or a total driving power of about 160 tons.

In these tunnels, what is known as the "assisted shield" method was adopted, when dealing with water-bearing strata. This method consisted in driving a small top heading, the roof of which was supported by poling boards with their rear ends resting on the shield. This heading was then widened out and protected by boards supported by raking struts from the cast iron lining. Lime grout was forced under pressure through holes in the poling boards, and this materially reduced the escape of the compressed air. The shield was then forced forward by means of the six rams, the stroke of which was $20\frac{1}{2}$ inches. At the ends of the ram pistons were fixed cast steel shoes, which distributed the pressure over the lining already fixed. The next length of lining was then put in under cover of the tail of the shield. The segments of the cast iron lining were 19 inches long and nearly 1 inch thick on the first section, and 20 inches long and $\frac{7}{8}$ inch and 15-16ths inch thick on the second section.

Grouting under compressed air was first successfully used in these tunnels. The apparatus used for grouting consists of a cylindrical vessel, which contains a mixture of lime and water, which is kept mixed by means of paddles to the consistency of thin cream. Compressed air is admitted through a pipe to the top of the vessel, and this forces the grout through a nozzle, which is inserted in holes in the cast iron segments left for the purpose. After experiment, lime was preferred to cement for this purpose. The grouting prevented the escape of the compressed air, and at the same time had an important effect in reducing settlement of the overlying material to a minimum.

The "assisted shield" method in loose strata is possible only with shields of small diameter, and it has decided disadvantages, inasmuch as the raking struts prevent the closing of the face in dangerous ground.

The construction of these tunnels has been dwelt on at some length because they were the first of the modern shield driven type. Though not next in chronological order, the Baker